

# NEOWISE-R Observation of the Coolest Known Brown Dwarf

Edward L. Wright<sup>1</sup>, Amy Mainzer<sup>2</sup>, J. Davy Kirkpatrick<sup>3</sup>, Frank Masci<sup>3</sup>, Michael C. Cushing<sup>4</sup>, James Bauer<sup>2</sup>, Sergio Fajardo-Acosta<sup>3</sup>, Christopher R. Gelino<sup>3</sup>, Charles A. Beichman<sup>3,5</sup>, M. F. Skrutskie<sup>6</sup>, T. Grav<sup>7</sup>, Peter R. M. Eisenhardt<sup>2</sup>, Roc Cutri<sup>3</sup>

wright@astro.ucla.edu

## ABSTRACT

The Wide-field Infrared Survey Explorer (WISE) spacecraft has been reactivated as NEOWISE-R to characterize and search for Near Earth Objects. The brown dwarf WISE J085510.83-071442.5 has now been reobserved by NEOWISE-R, and we confirm the results of Luhman (2014b), who found a very low effective temperature ( $\approx 250$  K), a very high proper motion ( $8.1 \pm 0.1$  "/yr), and a large parallax ( $454 \pm 45$  mas). The large proper motion has separated the brown dwarf from the background sources that influenced the 2010 WISE data, allowing a measurement of a very red WISE color of  $W1-W2 > 3.9$  mag. A re-analysis of the 2010 WISE astrometry using only the W2 band, combined with the new NEOWISE-R 2014 position, gives an improved parallax of  $448 \pm 33$  mas and proper motion of  $8.08 \pm 0.05$  "/yr. These are all consistent with Luhman (2014b).

*Subject headings:* brown dwarfs – astrometry – stars:individual WISE J085510.83-071442.5

## 1. Introduction

The Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010) observed the entire sky in four infrared bands at 3.4, 4.6, 12 and 22  $\mu\text{m}$  in early 2010, then continued to observe in the 3.4 and 4.6  $\mu\text{m}$  bands until Feb 2011. In Feb 2011 the spacecraft was placed into hibernation. In late 2012 a brief test showed that the spacecraft was still functional, and in 2013 the planetary science division of NASA funded a reactivation of the spacecraft to characterize and search for Near Earth Ob-

jects, with Amy Mainzer as Principal Investigator of this new NEOWISE-R (NEO WISE Reactivation) mission. After passively cooling back to 73 K, surveying the sky began again in December 2013 (Mainzer et al. 2014).

Both Luhman (2014a) and Kirkpatrick et al. (2014) noted that the source WISE J085510.83-071442.5 (also WISEA J085510.74-071442.5, hereafter W0855) had a large motion between the two epochs of WISE data in May and November 2010. But since the source could not be seen in the 2MASS survey (Skrutskie et al. 2006), this motion was unconfirmed. Luhman (2014b) also failed to see W0855 in the J band images from the VISTA survey (McMahon et al. 2013), but was able to obtain data using the short wavelength bands of the IRAC camera (Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) that confirmed the large motion and showed a large parallax as well. In addition, these data showed that W0855 was an extremely red source, and that a clump of background sources had influenced the WISE photometry and astrometry

<sup>1</sup>UCLA Astronomy, PO Box 951547, Los Angeles CA 90095-1547

<sup>2</sup>Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109

<sup>3</sup>Infrared Processing and Analysis Center, California Institute of Technology, Pasadena CA 91125

<sup>4</sup>Department of Physics and Astronomy, University of Toledo, 2801 W. Bancroft St., Toledo OH 43606-3328

<sup>5</sup>NASA Exoplanet Science Institute, MS 100-22, California Institute of Technology, Pasadena CA 91125

<sup>6</sup>Department of Astronomy, University of Virginia, Charlottesville, VA, 22904

<sup>7</sup>Planetary Science Institute, Tucson, AZ 85719

taken in 2010. The low luminosity and red color of W0855 require effective temperatures near 250 K and masses well below the deuterium burning limit: 3 to 10 Jupiter masses for ages of 1 to 10 Gyr (Luhman 2014b). Further observations of W0855 and further searches for similar objects will aid our understanding of the relation between the population of more massive brown dwarfs and the population of exoplanets both bound and free-floating (Sumi et al. 2011).

In May 2014 NEOWISE-R scanned over W0855 again, giving new unconfused position and photometry data for both W0855 and the clump of background sources. In this paper we use these data to derive an improved proper motion and parallax fit for W0855, and to derive uncontaminated colors in the WISE bands. Figure 1 shows postage stamps of the WISE W1 and W2 coadds for the three epochs. In addition we report an unsuccessful attempt to detect W0855 in the H band.

## 2. Observations

The 2014 NEOWISE-R data are reported in Table 1 and Table 2. These values were all obtained using the AllWISE profile fit photometry and astrometry software applied to the sets of frames containing W0855 in each epoch. The combined flux from W0855 and the background source clump gives a W2 magnitude of  $13.757 \pm 0.050$ , which is reasonably close to the  $13.633 \pm 0.038$  observed in May 2010. All magnitudes and colors in this paper are reported on the Vega system. The W1-W2 color observed in 2010 was clearly contaminated by the background source clump. The new color  $W1-W2 = 3.803 \pm 0.329$  mag is extremely red, placing W0855 squarely in the region of Y dwarfs (Kirkpatrick et al. 2012). The signal to noise ratio in W1 is quite low, so the limits on the color are asymmetric: at  $2\sigma$ , the range of colors consistent with the data is 3.3 to 4.8 mag. Examination of Figure 1 shows that the NEOWISE-R W1 flux may still be confused by a much fainter background source, and that the density of faint background objects is such that the W1 flux measurement of W0855 is confusion limited.

In order to reduce the effects of confusion, difference images of the May 2014 coadd minus the May 2010 coadd were constructed. These are shown in Figure 2. Analysis of these images shows

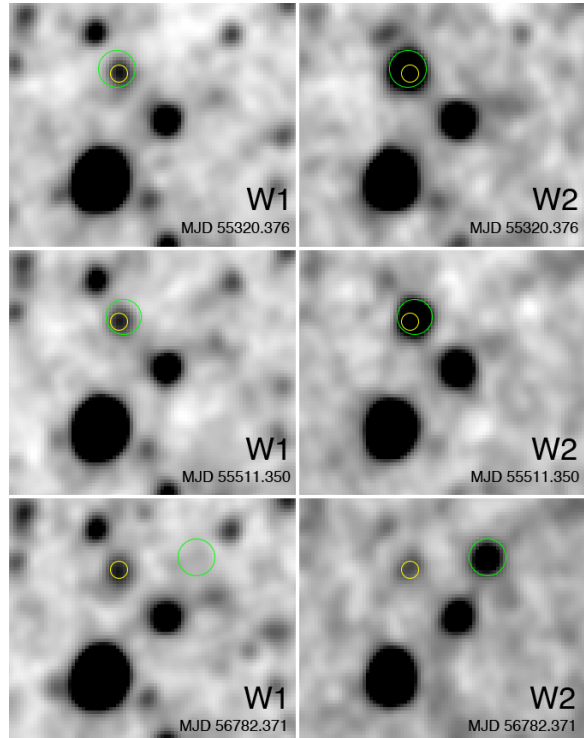


Fig. 1.— W1 and W2 images of the W0855 field for the three WISE epochs. The small yellow circle marks the background source clump. The larger green circle marks the WISE position for each epoch. Each panel is  $100''$  wide, with North at the top and East on the left.

that the W1 flux of W0855 is  $7.5 \pm 6.5 \mu\text{Jy}$ . This is about  $2.3\sigma$  less than the value found by the standard profile fit photometry, indicating that the May 2014 epoch probably still suffers from confusing background sources. The central value of the W1-W2 color is 5.0 mag, with a  $2\sigma$  lower limit on the color of 3.9 mag. W0855 is an extremely red source.

W0855 was observed on 9 Feb 2014 in the H ( $1.6 \mu\text{m}$ ) band with NIRC2 behind the Keck II LGS-AO system (Wizinowich et al. 2006; van Dam et al. 2006), but the  $40''$  field-of-view was improperly centered due to the large proper motion of W0855. W0855 was reobserved on 18 May 2014 but no detection was made in 30 minutes of integration, and a  $3\sigma$  upper limit is reported in Table 2. This upper limit shows that W0855 is redder than W1828+2650, one of the reddest known brown

Table 1: New Astrometric Data [J2000]

MJD	$\alpha$ [°]	$\sigma_\alpha$ [mas]	$\delta$ [°]	$\sigma_\delta$ [mas]	Notes
55320.376	133.7951649	101	-7.2451021	111	WISE W2 only
55511.350	133.7944072	109	-7.2450719	120	WISE W2 only
56782.371	133.7862181	158	-7.2442562	175	NEOWISE-R
56782.371	133.7949499	207	-7.2455978	231	Bkgnd, W1 & W2
56782.371	133.7949398	486	-7.2452772	556	Bkgnd, W2 only

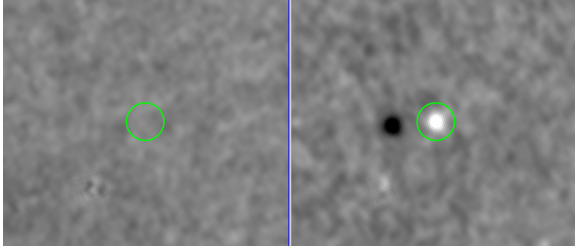


Fig. 2.— May 2014 minus May 2010 images. Left panel: W1, right panel: W2. Width of each image is 3.5'. The circle marks the May 2014 position of W0855.

dwarfs, in the H-W2 color (Kirkpatrick et al. 2012). The upper limit  $J > 23$  reported by Luhman (2014b) shows that W0855 is also nearly as red or redder than W1828+2650 in the J-W2 color.

Table 2: New Photometric Observations.

Filter	Magnitude	Notes
W1	$16.117 \pm 0.073$	Background Clump
W2	$15.441 \pm 0.152$	Background Clump
H	$> 22.7$	W0855
W1	$17.819 \pm 0.327$	W0855
W2	$14.016 \pm 0.048$	W0855

### 3. Astrometric Fit

Also reported in Table 1 are new analyses of the 2010 WISE data. For these positions, only the W2 data were used. Since the detection of W0855 is dominated by W2 and the detection of the background source clump is dominated by W1, the positions will be less effected by confusion.

Even with the positions derived from W2 data alone, we expect to see an astrometric shift due to the influence of the background source clump. Luhman (2014b) went to considerable lengths to

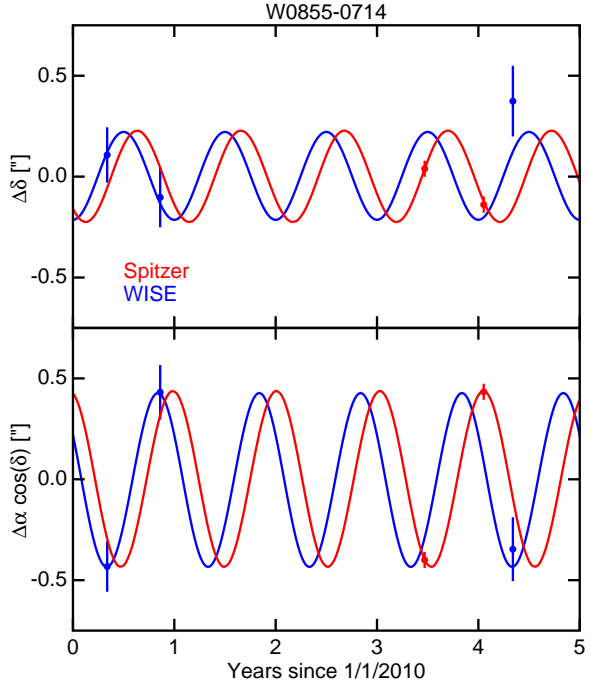


Fig. 3.— Astrometric data and fit for W0855. The constant and proper motion terms have been taken out in order to clearly show the parallax motion. The parallax curve for Spitzer has a different phase due to its Earth-trailing orbit.

correct for this influence. In order to check Luhman's analysis using an independent method, we use a fairly simple analysis where which assumes that the true position is related to the observed position by

$$(\alpha, \delta)_{\text{true}} = f \times (\alpha, \delta)_{\text{obs}} + (1-f) \times (\alpha, \delta)_{\text{bkgnd}} \quad (1)$$

We model the true position by the usual five parameters:  $\Delta\alpha_o$ ,  $\Delta\delta_o$ ,  $\mu_\alpha = \cos\delta \, d\alpha/dt$ ,  $\mu_\delta = d\delta/dt$  and parallax  $\varpi$ . This introduces a sixth parameter  $f$  into the analysis in addition to the usual five parameters. Only the first two observations by

WISE are affected by this new parameter.

We end up with the standard equations (Marsh et al. 2013) for  $i = 3$  to 5:

$$\begin{aligned} x_i &= \cos \delta_1 (\alpha_i - \alpha_{\text{bkgnd}}) \\ &= \Delta\alpha + \mu_\alpha (t_i - t_1) + \varpi \vec{R}_i \cdot \hat{W} \\ y_i &= \delta_i - \delta_{\text{bkgnd}} \\ &= \Delta\delta + \mu_\delta (t_i - t_1) - \varpi \vec{R}_i \cdot \hat{N} \end{aligned} \quad (2)$$

and modified equations for  $i = 1$  and 2:

$$\begin{aligned} x_i &= \cos \delta_1 (\alpha_i - \alpha_{\text{bkgnd}}) \\ &= \Delta\alpha + \mu_\alpha (t_i - t_1) + \varpi \vec{R}_i \cdot \hat{W} - (f - 1)x_i \\ y_i &= \delta_i - \delta_{\text{bkgnd}} \\ &= \Delta\delta + \mu_\delta (t_i - t_1) - \varpi \vec{R}_i \cdot \hat{N} - (f - 1)y_i \end{aligned} \quad (3)$$

where  $t_i$  is the observation time [yr] of the  $i^{\text{th}}$  astrometric measurement, and  $R_i$  is the vector position of the observer relative to the Sun in celestial coordinates and astronomical units.  $\hat{N}$  and  $\hat{W}$  are unit vectors pointing North and West from the position of the source. Epochs 3 & 4 are the Spitzer positions reported by Luhman (2014b).  $R_i$  is the position of the Earth for WISE observations; for Spitzer observations,  $R_i$  is the position of the spacecraft. The observed positional difference on the left hand side is in arcsec, the parameters  $\Delta\alpha$  and  $\Delta\delta$  are in arcsec, the proper motion  $\mu_\alpha$  and  $\mu_\delta$  are in arcsec/yr, and the parallax  $\varpi$  is in arcsec.

In 2010,  $x_i$  and  $y_i$  are small, and the value for the parameter  $f$  is close to one, so the non-standard terms  $(f - 1)x_i$  and  $(f - 1)y_i$  on the right hand side of Eqn 3 do not cause problems. But they do require inflating the standard deviations of the 2010 data points by a factor of  $f$ , since a change of  $x$  by  $f\sigma$  is necessary to change the left hand side of Eqn 3 by  $\sigma$ . An iterative cycle of fitting for  $f$ , reweighting, then refitting for  $f$  converges rapidly. In addition to this error inflation, there is an error with the form  $(f - 1)\sigma_{\text{bkgnd}}$  which is perfectly correlated across all the 2010 data. The background clump is faint in W2 leading to an imprecise position, but the W2 only position is not affected by color differences among the clump members. The effects due to the uncertainty in the clump position, the  $(f - 1)\sigma_{\text{bkgnd}}$  term, are significant and need to be added in quadrature to the errors from the

least squares fit. This was done by running the solutions for three background clump positions: the nominal position, a position with  $+1\sigma_\delta$ , and a position with  $+1\sigma_\alpha$ . Differences between these solutions give the sensitivity of the parameters to the background clump position errors. The final uncertainty on a parameter, such as  $\varpi$ , is given by  $\sigma(\varpi)^2 = \sigma(\text{LSQ})^2 + (\sigma(\delta_{\text{bkgnd}})\partial\varpi/\partial\delta_{\text{bkgnd}})^2 + (\sigma(\alpha_{\text{bkgnd}})\partial\varpi/\partial\alpha_{\text{bkgnd}})^2$ , where  $\sigma(\text{LSQ})$  is the usual error reported by the least squares fit. The resulting parameter values and uncertainties are  $\mu_\alpha = -8.051 \pm 0.047''/\text{yr}$ ,  $\mu_\delta = 0.657 \pm 0.050''/\text{yr}$ , parallax =  $448 \pm 33$  mas, and  $f = 1.237 \pm 0.071$ . For this fit  $\chi^2 = 2.59$  with 4 degrees of freedom. Figure 3 shows the data and the fit with the proper motion removed.

W0855 passed from East to West of the background clump during 2010, and the mean right ascension during 2010 is well determined. As a result our  $\mu_\alpha$  differs from Luhman's value by only 9 mas/yr, which supports our reduced uncertainty on  $\mu_\alpha$ . The proper motion in right ascension is highly correlated with the parallax, so by reducing the uncertainty in  $\mu_\alpha$  we also get a reduced uncertainty in the parallax. The difference between this paper and Luhman (2014b) in  $\mu_\delta$  is  $43 \pm 86$  mas/yr when we use the W2 only position for the clump of background sources.

The value of  $f$  implies that the centroid is a weighted sum of W0855 and the background source clump with weights  $1/f = 81 \pm 4\%$  for W0855 and  $19 \mp 4\%$  for the background source clump. The total W2 flux is divided with  $79 \pm 2.5\%$  from W0855 and  $21 \mp 2.5\%$  from the background source clump. Thus the derived value for  $f$  is reasonable.

Our conclusion about the astrometry of W0855 is that Luhman's procedure for correcting the 2010 data for the effect of the background source clump was quite successful, and our new data and independent analysis technique give a parallax only 6 mas different than Luhman (2014b). Further astrometry of W0855 could reduce our reliance on the confused WISE 2010 data, and this may come from NEOWISE-R which should get 5 more epochs, from further Spitzer observations, or from HST detections of the J or H band flux.

#### 4. Discussion

The  $\geq Y2$  brown dwarf W1828+2650 is so faint at J and H that the HST is needed to measure an accurate color:  $F140W-W2 = 8.76 \pm 0.11$  mag for this very red object. But W1828+2650 is not extremely low luminosity given its absolute magnitude  $M_{W2} = 14.17 \pm 0.25$  (Beichman et al. 2013). The distant white dwarf companion WD0806-661B has  $F125W-[4.5] = 8.81 \pm 0.14$  mag (Gelino et al. 2014; Luhman et al. 2012) but an absolute magnitude  $M_{4.5} = 15.46 \pm 0.07$  (Luhman et al. 2012). On the other hand the Y1 brown dwarf W0350-5658 is bluer, with  $F140W-W2 = 7.57 \pm 0.21$  mag, but much less luminous with  $M_{W2} = 17.05 \pm 0.38$  (Marsh et al. 2013). Thus W0855, with  $M_{W2} = 17.27 \pm 0.17$ , is less luminous than the least luminous previously known brown dwarfs, and as red or redder than the reddest previously known brown dwarfs. Many more objects redder than W0855 or less luminous than W0855 are needed to understand the trend and scatter of the luminosity *vs.* color relation for these very low luminosity objects.

We are fortunate that W0855 is approximately 2 magnitudes above the AllWISE catalog limit, so a full search of the entire catalog would cover a volume  $(10^{0.8})^{1.5} = 15.85$  larger than the volume of the sphere containing W0855. Thus there is a good possibility that many more examples of W0855-like objects exist in the AllWISE catalog, but in the absence of a third epoch to confirm the existence of a moving W2 only source it is not practical to obtain followup data from Spitzer or any ground-based telescope. The “statistics of one” limit the precision of any estimated number, but Kerman (2011) recommends using a  $\lambda^{-2/3}$  prior for the Poisson rate  $\lambda$ , which gives a posterior probability density  $\propto \lambda^{1/3} \exp(-\lambda)$  when  $n = 1$  objects have been seen. This posterior has its 16<sup>th</sup> %-tile at 0.33, its median at  $n = 1.01$ , and its 84<sup>th</sup> %-tile at 2.33. With this posterior we estimate the number of objects that a survey of 15.85 times more volume would see, again using a Poisson distribution. This calculation gives a 16<sup>th</sup> to 84<sup>th</sup> %-tile range of 4 to 35, with a median of 15.

The combination of NEOWISE-R data with the AllWISE database will provide the additional observation epochs needed to confirm AllWISE motion detections of low SNR sources, making it

practical to find more W0855-like objects if they exist.

#### 5. Conclusion

Early data from NEOWISE-R have provided new astrometric and photometric parameters for W0855. These are all consistent with the results of Luhman (2014b), and confirm that W0855 is an extremely red object with an extremely faint absolute magnitude  $M_{W2} = 17.27 \pm 0.17$ . W0855 shows that a population of very cold brown dwarfs exists that are so red that they are effectively unobservable from the ground at near-IR wavelengths. Since W0855 is two magnitudes brighter than the detection limit of WISE in the W2 band, an astrometric analysis of all the NEOWISE-R data down to the catalog limit could lead to the discovery of 4-35 similar objects.

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